Renewable Energy 116 (2018) 827–834

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Review

Impacts of climate change, policy and Water-Energy-Food nexus on hydropower development

Xiao Zhang [a], Hong-Yi Li [a, b, *], Zhiqun Daniel Deng [a], Claudia Ringler [c], Yang Gao [d], Mohamad I. Hejazi [e], L. Ruby Leung [d]

[a] Hydrology Technical Group, Pacific Northwest National Laboratory, Richland, WA, USA
[b] Now at Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, MT, USA
[c] International Food Policy Research Institute, Washington D.C., USA
[d] Atmospheric Sciences and Global Change Division, Pacific Northwest National Laboratory, Richland, WA, USA
[e] Joint Global Change Research Institute, College Park, MD, USA

ARTICLE INFO

Article history:
Received 13 June 2017
Received in revised form
11 September 2017
Accepted 9 October 2017
Available online 10 October 2017

Keywords:
Hydropower
Water-food-energy nexus
Climate change
Sustainability

ABSTRACT

Hydropower plays an important role as the global energy system moves towards a less carbon-intensive and sustainable future as promoted under the Sustainable Development Goals (SDGs). This article provides a systematic review of the impacts from policy, climate change and Water-Energy-Food (W-E-F) nexus on hydropower development at global scale. Asia, Africa and Latin America are hotspots promoting hydropower development with capacity expansion, while Europe and North America focus on performance improvement and environment impacts mitigation. Climate change is projected to improve gross hydropower potential (GHP) at high latitude of North Hemisphere and tropical Africa and decrease that in the US, South Africa and south and central Europe. Analysis from W-E-F nexus highlights the importance of integrated approaches as well as cross-sectoral coordination so as to improve resources use efficiency and achieve sustainable hydropower development. These three factors together shape the future of hydropower and need to be considered for planning and operation purpose.

Contents

1. Introduction

Hydroelectricity generation has doubled during the last thirty years and is projected to double the current production level by 2050 [1]. It contributes to base load and provides flexibility to meet peaks in demand, which has improved electric grid stability and reliability and fostered energy security [2,3]. In 2012, global hydroelectricity generation reached 3646 TWh, which accounted for about 77% of total renewable electricity generation and supplied 18% of total electricity consumption. Asia, Latin America as well as North America contribute over 70% of global hydropower generation, while Middle East and Africa produce less than 5% (Fig. 1). The three largest producers, China, Brazil and Canada account for over

* Corresponding author. Hydrology Technical Group, Pacific Northwest National Laboratory, Richland, WA, USA.
E-mail address: hongyi.li@montana.edu (H.-Y. Li).

https://doi.org/10.1016/j.renene.2017.10.030

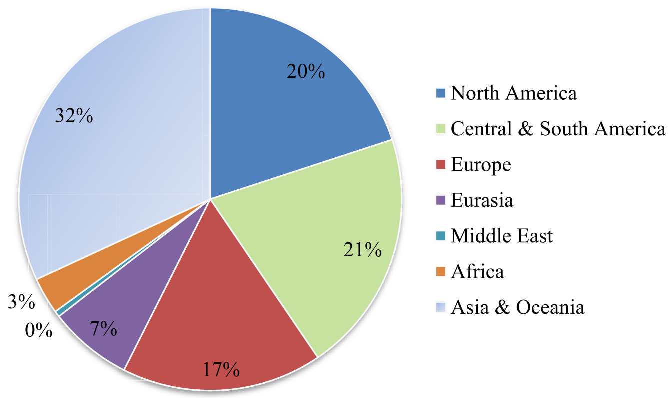

Fig. 1. Share of hydroelectricity generation by continent, average of 2008–2012 (own figure based on data from Ref. [4].

40% of current hydropower generation. Hydropower plants with reservoirs can improve energy supply security and reliability [5]. Despite possible methane emissions from the impounded areas, carbon emissions from hydropower reservoirs are relatively low in comparison to other technologies [6,7]. It is therefore considered to be an essential element of the future energy mix as the global energy system moves towards a less carbon-intensive and sustainable future.

The Water-Energy-Food (W-E-F) nexus describes interactions among water, energy and food [8]. The numerous interconnections within the nexus represent the complex and inter-related nature of the coupled human-nature system. A nexus perspective helps to build synergies and to identify and manage tradeoffs, enabling more integrated and cost-effective planning and implementation [9]. Hydropower is one critical component within the nexus, interacting with other sectors constantly (Fig. 2). It utilizes falling water or fast running water to generate energy. At the same time, large-scale hydropower infrastructure provides water storage for irrigation downstream [10–13]. It also affects fish production, with potential increases in the reservoirs, and migration, with likely adverse impacts through interrupting migration routes, thereby affecting food production in differential ways in different geographies [14,15]. With rapid population growth and socio-economic development and additional pressures from climate change, the interactions between hydropower and other sectors within the nexus will increase in both intensity and frequency [16,17]. A nexus approach will therefore be of great utility to achieve various social, economic and environmental goals, thus contributing to achieving the targets of key SDGs [17–20].

Development of hydropower is affected by investment plans and hydrologic conditions. Climate change alters the annual mean and seasonality of runoff, all of which influence the availability and stability of hydroelectricity production and at the same time increase the value of the storage role that hydropower reservoirs have always had. In fact, glacier melt and growing water variability as a result of climate change are one of the main drivers for a revival in surface storage (and thus hydropower) development because of the inherent, crucial buffer function of storage [21–23]. Uncertainty associated with climate change also poses great risks and challenges for hydropower planning and management [22].

Policy and investments are the main driving forcing of hydropower development and determine the geographical difference in

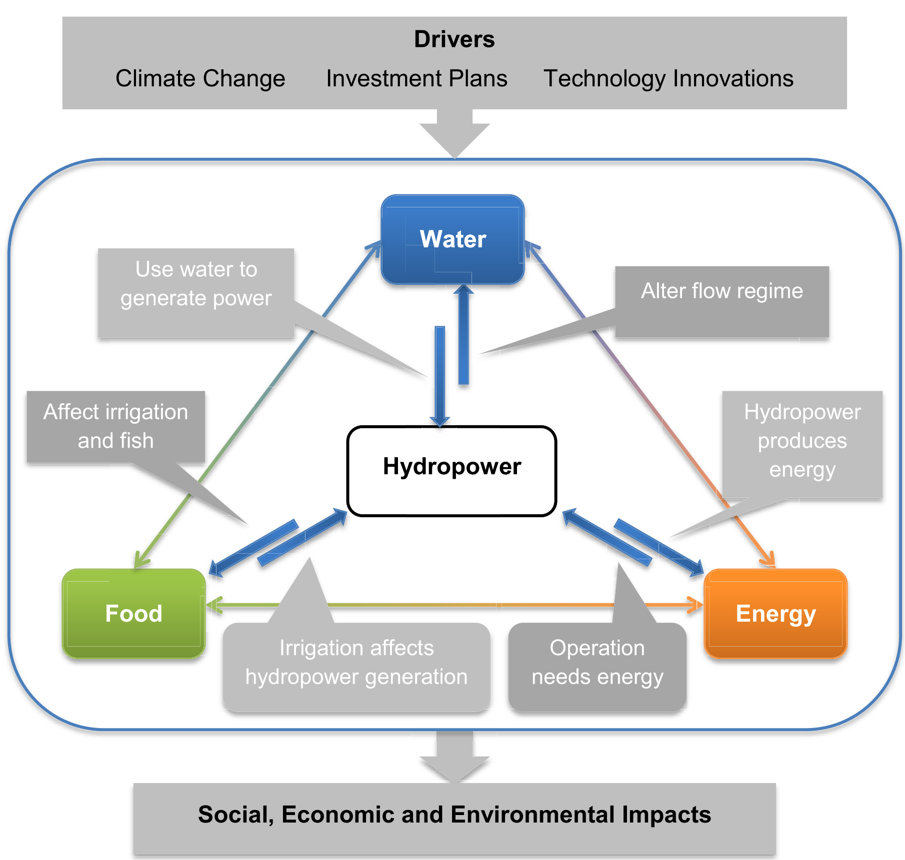

Fig. 2. Hydropower development considering interactions within the W-E-F Nexus.

development level. Climate change affects gross potential of hydropower through altering streamflow regime. W-E-F nexus constrains or promotes hydropower development via interactions with environment and human society. Previous studies discussing hydropower's future mostly focused on policy projections or hydrologic changes [3,5,15,24–28]. To our knowledge, so far there has been no effort to review the impacts of the Water-Energy-Food nexus on hydropower development. This article provides a comprehensive review of hydropower's prospects from three facets: investment trends, climate change and the W-E-F nexus effects (Fig. 2). Insights from these three perspectives help provide valuable guidelines for hydropower planning and implementation so as to support adaptation to and mitigation of adverse climate change impacts as well as socio-economic development.

2. Policy and investment trends

Governments are the key investment agencies of hydropower projects [5]. Many countries have short-term, medium and long-term plans for hydropower development. This section reviews the investment plans in six regions: Africa, Asia, Oceania, Europe, Latin America and North America, which are characterized by different development potential and status. General trends in government and institution's preferences of hydropower are also discussed.

Africa is currently the least developed region in terms of hydropower development. Its technical potential for hydropower is similar to that of Europe, but only 8% has been exploited as of 2009 [29]. Meanwhile, less than 15% of the rural population in Sub-Saharan Africa has access to electricity [30]. In order to address the electricity shortage situation in the region, projects at various scales are currently proposed or under development. In 2011, the Democratic Republic of Congo (DRC) proposed the Grand Inga project with a potential capacity of 39,000 MW, which is more than double of the hydroelectricity generated by Three Gorges Dam on the Yangtze River in China. Once completed, it would be the largest hydropower facility on earth. Another controversial hydropower scheme under development is the Grand Ethiopian Renaissance Dam (GERD) in Ethiopia on the Nile River. The installed capacity is 6450 MW and it is able to greatly improve electricity supply in Ethiopia and neighboring countries. GERD would reduce flooding downstream but also cause significant decrease in downstream water availability as well as irrigated areas [31]. However, most projects that are being developed are at a smaller scale. Small- and medium-scale projects are likely to play a greater role in the future due to their economic viability and higher level of local acceptance [32]. Investment increases, together with technical improvement, might well increase hydroelectricity generation to 30% of its technical potential in Africa by 2050 [1]. The regulatory framework in most countries is the Act of parliament, which aims at reliable and affordable power supply. The regulations of small hydropower projects may be relaxed to attract private sector participation and financial flow [33].

Asia is the region with the richest hydropower potential and has the largest installed capacity by far. China, in particular, in 2014 had about 280 GW installed hydropower capacity and contributes over 20% of global hydroelectricity production [34]. In 2007, the National Development and Reform Commission of China launched the Medium and Long-term Plan to increase the installed capacity of hydropower to 300 GW by 2020, with 225 GW from large and middle-scale projects and 75 GW from small projects [27,35]. The Ministry of Water Resources of China provides low-interest loans of about 26 million USD for small hydropower development [36]. Other countries in South and Southeast Asia also proposed to develop hydropower projects at various levels: Myanmar aims to increase its hydroelectricity generation from 365 MW in 2000 to 39,600 MW in the next two decades, India has projects of 13.9 GW under construction, Pakistan proposes a series of large-scale dams with over 25 GW capacity in total, Bhutan also has projects of 1.2 GW potential under construction [25]. By 2050, hydroelectricity generation is going to be doubled in Asia [1].

Australia has relatively low hydropower potential and hydroelectricity accounts for less than 5% of its current energy supply [24]. Given the scarcity of water resources, the potential for large-scale hydroelectricity facilities is limited. In comparison, small-scale hydropower is likely to grow in capacity [24]; [34]. By 2030, hydroelectricity generation may anticipate slight increase from 12 TWh in 2007 to 13 TWh, but its share compared to total electricity generation would decline [37]. By contrast, New Zealand generated 23 TWh of hydroelectricity in 2012 and several projects have been proposed to expand hydropower.

Europe generated 596 TWh of hydroelectricity in 2012, which utilizes 53% of its technical potential. In particular, one third of the untapped potential is in Turkey [1]. The current installed capacity of Turkey is 14 GW and it is projected to increase to 21 GW by 2020 [38]. Organization for Economic Co-operation and Development (OECD) countries in Europe only anticipate a 0.8% increase in hydroelectricity by 2035 [29]. Instead of constructing large-scale conventional hydropower, Europe is at the forefront of promoting a variety of renewables, such as open-loop or pump back pumped storage plants (PSP) [1]. Furthermore, there is a tendency to focus on the environmental impact and ecology preservation in hydropower assessment [1,25,39].

Latin America is blessed with rich hydropower resources and hydroelectricity strongly contributes to this region's energy mix, with over 70% of electricity derived from hydropower. A total of 715 TWh of hydroelectricity was produced in 2012, over half of which was from Brazil. Installed capacity in Brazil was 82 GW in 2011 and is projected to reach 115 GW in the near future according to Brazil's 10-year energy plan 2020 [1]. Other countries, including Chile, Colombia, Costa Rica, Ecuador and Peru also launched ambitious hydropower development plans to increase installed capacity [40]. Since this region has large areas of tropical rain forest, which plays a significant role in the water and carbon cycles as well as biological diversity, it is important to incorporate environmental assessments such as those detailing potential deforestation effects and impacts on aquatic and other ecosystems into the decision making process [41].

Canada and the United States contributed to 21% of global hydropower generation in 2010, and 60% of the technical potential remains untapped [23]. Resource assessments by the U.S. Department of Energy show that it is possible to double hydropower capacity in the U.S. by optimizing or upgrading existing facilities, powering non-powered dams, as well as developing new hydropower facilities on streams and in conduits and canals [1,42]. Based on a quantitative analysis of U.S. energy incentives from 1950 to 2010, around 87% of incentives for hydroelectricity come from market activity and tax policy [43]. Tax policy includes credits, allowances, deductions etc., and market intervention incentives for hydroelectricity refer to the prorated costs of construction and operation of dams. About 60% of Canada's electricity is currently generated from hydropower. The country aims to achieve a sustainable energy future by promoting renewables, including hydroelectricity [44]. Capital investment has been made not only to performance improvement but also environmental impacts mitigation and this trend is likely to continue as promoted in the North America Clean Energy Plan [45].

Fig. 3 summarizes current and planned hydropower generation compared to the estimated technical potential. Asia expects to remain as the hotspot of hydropower development. Since hydropower is relatively affordable and its construction promotes

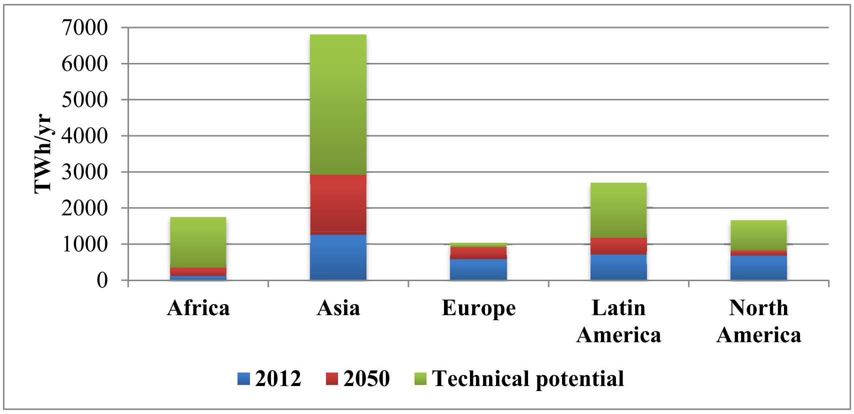

Fig. 3. Current and planned hydropower generation [1,46] compared with technical potential [25].

industrialization, many developing countries rely on hydropower to improve energy supply and reduce poverty [5,25]. It is also attractive because life cycle GHG emissions of hydropower, run-of-river power plants in particular, are relatively low compared to other energy sources [7]. Nevertheless, there has been a lot of controversy surrounding large-scale hydropower infrastructure, mainly due to environmental concerns such as sediment transport and adverse river ecology impacts [25]. Other important concerns include needs for resettlement and environmental destruction of neighboring areas, when construction is planned in sensitive environments [47]. There have been growing concerns related to construction on transboundary rivers, including on rivers that are also country boundaries. In comparison, small hydro plants are gaining in popularity and are recognized as a growing source of rural electricity supplies, due to better economic viability, higher level of local acceptance and lower pressure on the environment [32,48].

3. Climate change impact

Climate change affects hydroelectricity generation mainly through streamflow. It is projected that climate change may increase global gross hydropower potential (GHP) by 2.4–6.3% [49] but reduce global annual generation capacity of existing hydropower plants by 0.4–6.1% for the 2080s compared to 1971–2000 mainly due to the heterogeneity of topography and climate change effects [28]. An earlier study projected negligible change in hydropower generation by the 2050s [22]. Trends and patterns of changes in GHP overall reflect the changes in streamflow. In general, high latitude areas in the Northern Hemisphere and tropical regions may anticipate increases in GHP. Other regions such as U.S., central and south Europe, and the most southern parts of South America, Africa and Australia are likely to decreases in GHP due to streamflow reduction [22,49]. Although the global mean streamflow is projected to increase, most hydropower plants are located in areas with expected declines in mean annual streamflow, which results in a decrease in the global hydropower generation capacity [28]. The differences in future hydropower capacity and potential are mainly caused by the uncertainties associated with the different climate models, various parameterization and structure of hydrological models as well as different greenhouse gas emission scenarios [49].

Here we adopt runoff projections from a multi-model ensemble of simulations from Coupled Model Intercomparison Project Phase 5 (CMIP5) [50] to simulate the impacts of climate change on gross hydropower potential, as shown in Fig. 4. Two Representative Concentration Pathways (RCP) scenarios are selected to cover both the low-to-medium emission scenario (RCP4.5) and the fossil fuel intensive scenario (RCP8.5) [51,52]. Historical runoff is the composite data from The International Satellite Land Surface Climatology Project (ISLSCP) II [53]. Streamflow is obtained using linear reservoir routing [54] based on flow directions developed using hierarchical dominant river tracing (DRT) [55]. GHP is calculated as a linear function of streamflow [56] given the assumption that elevation difference does not change with time. Fig. 3 illustrates the mid-term (2041–2060) and long-term (2080–2099) changes in GHP derived from the changes of streamflow under RCP4.5 and RCP8.5 respectively compared to 1981–2000. Consistent with the overall pattern of precipitation changes projected by the climate models of "wet gets wetter and dry gets drier" [57], increases in the GHP are likely at high latitudes of the Northern Hemisphere (i.e., Canada and Eurasia), tropical area in Africa while decreases are expected in the U.S., southern and central Europe, as well as South Africa. The pattern is similar to the findings reported in Ref. [49]; and is exacerbated in magnitude with time as warming increases with increasing CO_2 concentration through the 21st century. It should be noted that the increased hydropower potential in many regions might not be fully exploitable if no facility is available to store and utilize the additional water. Furthermore, with the increase in extreme precipitation [58,59] and more frequent and intense drought [e.g. [60]] projected for the future, managing the dams for hydropower production, irrigation and other uses will be more challenging. Assessing the changes in hydropower potential must consider not only changes in the mean annual and seasonal runoff, but also changes in both wet and dry extremes, which would require more sophisticated modeling and analysis methods and is a subject of ongoing research.

It is worth noting that climate change alters both energy demand and generation at the same time. The intensity and frequency of peak electricity demand are projected to increase significantly due to climate change across the United States [16]. It is probable that the seasonality changes of streamflow and peak demand do not align in many regions, which would pose greater stress on the electricity grid. Therefore, it is essential to consider intra-year dynamics [61] for power grid planning and operations.

4. The Water-Energy-Food nexus effects

Hydropower is a central node in the W-E-F nexus and closely connected with other sectors (Fig. 2). The linkages between hydropower and other nexus sectors are intertwined: hydropower can support water, energy and food security, but depending on

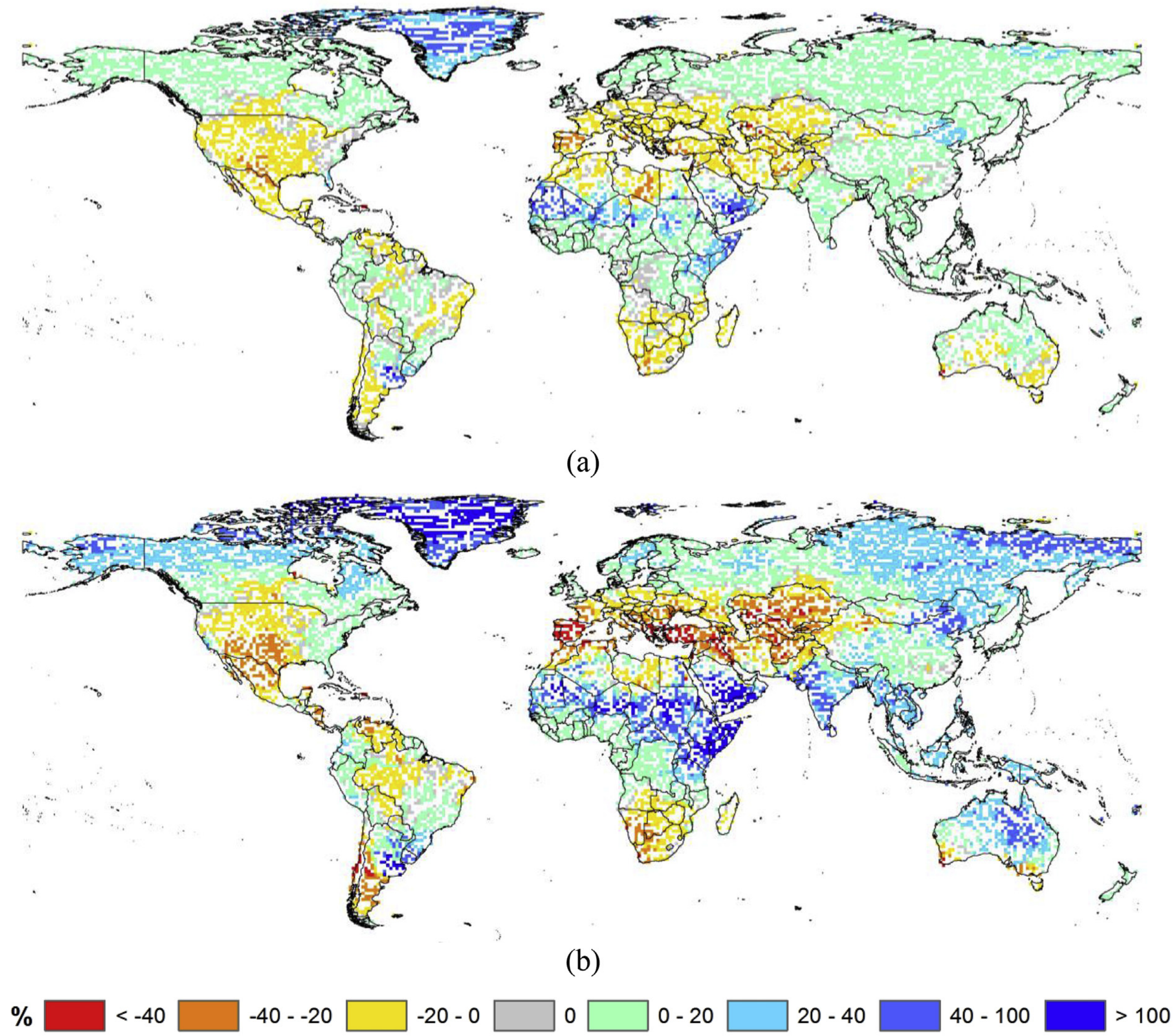

Fig. 4. Changes in gross hydropower potential (%) under climate change relative to 1981–2000 (a: 2041–2060 under RCP4.5, b: 2080–2099 under RCP8.5).

location and other factor; it could also constrain energy and food security, for example, affecting fishery and thus food security. As the competition for water among energy, food and environmental users increases with socioeconomic development and population growth, planning and management of hydropower needs to evolve to adapt with changes in both natural and anthropogenic conditions [12,62–64]. The W-E-F nexus could be an effective vehicle for improving resource use efficiency and advancing sustainable development of hydropower [8,13,20]. This section discusses both the synergies and tradeoffs of hydropower and other sectors within the nexus.

Hydropower reservoirs store water that can be used for other uses such as irrigation, industry and domestic supplies. Since many hydropower infrastructures are located in mountainous upstream areas where they consume little water, the water released to generate hydroelectricity remains available for irrigation in the downstream areas, but likely at time intervals that differ from natural flows. In many regions, and especially in developing countries, hydropower development has the potential to improve local or regional energy supply and crop production but might adversely impact fisheries production [65]. Here Ethiopia and Nam Ngum River in the Mekong Basin are used to illustrate the possible synergies between water, energy and food.

Ethiopia is one of the largest but least developed countries in Africa. Only 5% of plots or about 300,000 ha in the country currently receive any form of irrigation, contributing to cyclical food insecurity and variations in both agricultural and overall GDP as a result of the large share of employment in the sector and continued significant contribution to overall GDP. At the same time, in 2012 only 7.6% of the rural population had access to electricity [66] and the energy supply depends heavily on hydroelectricity with most of electricity generation stemming from hydropower [4]. The current hydroelectricity production accounts for only 2% of technical hydropower potential [40]. The high poverty, low energy security, and low agricultural water use as well as water stress can all be traced to under-investment in water and energy infrastructure [67]. Development of additional reservoirs has great potential to benefit both energy supply and food production considering its energy source structure [5]. Irrigation schemes can be considered as add-ons to hydropower, which generate side benefit and improve food security [68]. Notable efforts have been made to realize such synergies. The under-construction Grand Ethiopia Renaissance Dam expects to greatly improve energy supply in Ethiopia and neighboring countries. The planned max installed capacity is 6 GW compared to

the less than 1 GW installed capacity in Ethiopia in 2008.

The Nam Ngum River Basin, a tributary of the Mekong, is located in Lao PDR and covers 2% of the Mekong Basin's surface area. Agriculture is the major economic activity in the basin. Four hydropower dams are in operation and six new hydropower projects are slated for implementation in the upstream of the basin within the next 10 years [69]. Lacombe et al. investigated how hydropower development would affect irrigation in the Nam Ngum River Basin [70]. They found that full hydropower development increases river flow during dry season and would further improve the water availability for irrigation. One thing to notice is that this estimate only considers development impacts within the Nam Ngum subbasin. Collective influences in the wider Mekong basin would need additional research.

As food and energy demand grow rapidly with population growth and economic development, more concerns emerge to fight for limited, shared water resources. As a result, conflicts between hydropower and irrigation have gained a lot of attention. Upstream-downstream interest conflict and difference in water demand timing are two main reasons of conflicts. Diversion of water for irrigation upstream may reduce the water available to generate energy downstream. On the other hand, holding water in hydropower reservoirs to satisfy peak energy demand may leave less water to satisfy irrigation requirement during the crop growth season. A classic example is the Aral Sea region in Central Asia [71,72]. In upstream Tajikistan, energy demand is highest during winter for heating, while irrigation demand is largest during summer growth period. In Soviet times, upstream country provided water and hydroelectricity for irrigation downstream, and downstream countries compensated upstream with gas and oil for use during the winter [72]. However, the collaboration ceased after independence. As a result, upstream country now release water from reservoirs during the winter season to generate hydroelectricity and store summer flow, causing damage to irrigation infrastructure in winter and great losses in crop production and income of downstream countries during the summer season.

Energy-food tradeoffs are not uncommon. Another important example of the Water-Energy-Food linkages is the Mekong River basin, home of the biggest inland fishery in the world [15]. It originates from the Tibetan Plateau in China and flows toward the South China Sea, passing through Myanmar, Laos, Thailand, Cambodia and Vietnam. There are currently 32 hydropower dams in operation with an installed capacity greater than 10 GW. Laos proposed 11 dams along the lower Mekong and Cambodia proposed 2 dams on the mainstream Mekong as well. At the same time, another 78 tributary dams are planned besides the hundreds of small-scale hydropower dams in operation [26]. The large-scale development of hydropower projects will adversely affect endemic, migratory fish species, resulting in negative impacts on fisheries and thus protein or nutrition security of the local population. Hydropower construction is also detrimental to sediment deposits in the delta, leading to reduced agricultural productivity from reduced flooding, land loss to the sea in the delta, and further declines in fisheries biodiversity as important nutrients attached to the sediments remain trapped in the reservoirs ([26,73]. Significant increases in land and water use would be needed to replace the lost fish protein and satisfy food requirements [51]. As a consequence, local food security is at risk and the rural poor population would be particularly negatively affected since they rely on fisheries as a common income source and do not have sufficient financial or technical resources to adapt to the forthcoming changes [73,74]. Resettlement to allow for dam development along the river also affects the rural poor in the region.

Issues on how to promote potential synergies and manage tradeoffs related to hydropower in the W-E-F nexus pose great challenges to hydropower planning and management. Studies on water management have found some useful measures to deal with conflicts between irrigation and hydropower through dynamic management approaches that constantly adjust water allocation decision to improve the utilization efficiency of water resources. A case study on a cascade of multipurpose reservoir in Euphrates river basin concluded the dynamic allocation process improved the annual benefits by 6% compared to the static allocation [12]. Systems thinking methods such as causal loop diagram (CLD) [17] and cyber-physical framework [75] help capture the complexity of interactions among the various components in the system and identify key feedbacks as well as relative dominance [76]. Water rights and trade would furthermore allow water users to reallocate water through markets, which could be another valuable measure to tackle the tradeoffs among various stakeholders [77]. Multi-objective optimization is also a useful approach because it can be used to compare various development scenarios and facilitate tradeoff analysis [18,78], but it is challenging to reach a win-win scenario across the WFE nexus especially in transboundary river basins [19]. Furthermore, integrated modeling and cross-sectoral coordination are essential to reduce risks and uncertainties in design and implementation [9]. Solutions could be found within the nexus, such as a return for downstream countries in Central Asia to sending energy supplies upstream to ensure that water releases could be re-directed to the summer months critical for downstream irrigated food production; or could lay entirely outside the nexus, such as through monetary compensation, or other negotiated compensation. Clearly, to achieve overall gains and minimize likely growing future tradeoffs along the nexus, hydropower development should be preceded with consultations across all stakeholders relying on shared water resources, that is, the agriculture sector, cities and industries, but also fisheries and representatives of aquatic and other biodiversity.

5. Conclusions

As a well-established renewable energy source, hydropower will likely play a great role in the future as the energy system shifts towards a less carbon-intensive future and focuses on sustainable development. Hydropower development does not only improve energy supply and thus contribute to the energy SDGs, but it can also reduce poverty through myriad of other uses embedded in the storage that production generally, but not always, entails. Climate change remains a key driver for additional development due to the important buffer function of associated storage. It is expected to reduce existing global hydropower capacity but increase gross hydropower potential, which provides helpful implications for siting of new development. Interconnections of hydropower with other sectors in the W-E-F nexus will increase due to the growing energy and food demands, fostering more synergies and conflicts within the nexus.

The varieties in hydrological conditions, topography, financial capability, project size, climate change effects, nexus interconnections and environmental impacts make case-by-case analysis essential for hydropower planning. It is also of great importance to incorporate uncertainty assessment and risk analysis due to the inherent uncertainty associated with climate change. Extreme events need to be taken into account during hydropower development to mitigate possible adverse influences as climate change would increase the intensity and frequency of extreme climate conditions. Hydropower generates considerable social and environmental influences, which should be taken into account during project planning and management processes to minimize adverse effects and elevate overall welfare. A nexus perspective is of significant value to build synergies and manage tradeoffs for

hydropower planning and management. Dynamic and integrated approaches as well as cross-sectoral coordination are recommended to improve resources use efficiency and optimize overall benefits.

Acknowledgement

This study is supported by the U.S. Agency for International Development (USAID). The authors' views expressed in this publication do not necessarily reflect the views of USAID or the U.S. government. The Pacific Northwest National Laboratory is operated for the U.S. Department of Energy by Battelle Memorial institute under contract DE-AC05-76RLO 1830.

References

[1] International Energy Agency, Technology Roadmap: Hydropower, International Energy Agency, France, 2012.
[2] R. Sternberg, Hydropower: dimensions of social and environmental coexistence, Renew. Sustain. Energy Rev. 12 (2008) 1588–1621.
[3] I. Yüksel, l Hydropower for sustainable water and energy development, Renew. Sustain. Energy Rev. 14 (2010) 462–469.
[4] EIA, International Energy Statistics. U.S. Energy Information Administration, U.S. Department of Energy, Washington, D.C, 2015. http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=2&pid=2&aid=12.
[5] R. Sternberg, Hydropower's future, the environment, and global electricity systems, Renew. Sustain. Energy Rev. 14 (2010) 713–723.
[6] L. Gaudard, F. Romerio, Reprint of "The future of hydropower in Europe: interconnecting climate, markets and policies", Environ. Sci. Policy 43 (2014) 5–14.
[7] H.L. Raadal, et al., Life cycle greenhouse gas (GHG) emissions from the generation of wind and hydro power, Renew. Sustain. Energy Rev. 15 (7) (2011) 3417–3422.
[8] R. Lawford, et al., Basin perspectives on the Water-Energy-Food security nexus, Curr. Opin. Environ. Sustain. 5 (2013) 607–616.
[9] FAO, The Water-Energy-Food Nexus: a New Approach in Support of Food Security and Sustainable Agriculture, Food and Agriculture Organization of the United Nations, Rome, 2014.
[10] G. Rasul, Food, water, and energy security in South Asia: a nexus perspective from the Hindu Kush Himalayan region, Environ. Sci. Policy 39 (2014) 35–48.
[11] C.C. Tan, T. Erfani, R. Erfani, Water for energy and food: a system modeling approach for Blue Nile River Basin, Environments 4 (1) (2017) 15.
[12] A. Tilmant, Q. Goor, D. Pinte, Agricultural-to-hydropower water transfers: sharing water and benefits in hydropower-irrigation systems, Hydro. Earth. Syst. Sci. 13 (2009) 1091–1101.
[13] Y.C.E. Yang, et al., Modeling the agricultural Water-Energy-Food nexus in the Indus River Basin, J. Water Res. Plan. Man. 142 (12) (2016), 04016062.
[14] P.J. Dugan, et al., Fish migration, dams and loss of ecosystem services in the Mekong Basin, Ambio 39 (4) (2010) 344–348.
[15] G. Ziv, et al., Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin, Proc. Natl. Acad. Sci. U. S. A. 109 (2012) 5609–5614.
[16] M. Auffhammer, P. Baylis, C.H. Hausman, Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States, Proc. Natl. Acad. Sci. U. S. A. 114 (8) (2017) 1886–1891.
[17] J. Pittock, D. Dumaresq, A.M. Bassi, Modeling the hydropower-food nexus in Large River basins: a Mekong case study, Water 8 (10) (2016) 425.
[18] M. Bazilian, et al., Considering the energy, water and food nexus: towards an integrated modelling approach, Energy Policy 39 (12) (2011) 7896–7906.
[19] S. Jalilov, et al., Managing the Water-Energy-Food nexus: gains and losses from new water development in Amu Darya River Basin, J. Hydrol. 539 (2016) 648–661.
[20] C. Ringler, A. Bhaduri, R. Lawford, The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency? Curr. Opin. Environ. Sustain. 5 (2013) 617–624.
[21] T.P. Barnett, J.C. Adam, D.P. Lettenmaier, Potential impacts of a warming climate on water availability in snow-dominated regions, Nature 438 (2005) 303–309.
[22] B. Hamududu, A. Killingtveit, Assessing climate change impacts on global hydropower, Energies 5 (2012) 305–322.
[23] M.W. Rosegrant, C. Ringler, T. Zhu, Water for agriculture: maintaining food security under growing scarcity, Annu. Rev. Environ. Resour. 34 (2009) 205–222.
[24] A. Bahadori, G. Zahedi, S. Zendehboudi, An overview of Australia's hydropower energy: status and future prospects, Renew. Sustain. Energy Rev. 20 (2013) 565–569.
[25] Darmawi, R. Sipahutar, S.M. Bernas, M.S. Imanuddin, Renewable energy and hydropower utilization tendency worldwide, Renew. Sustain. Energy Rev. 17 (2013) 213–215.
[26] R.E. Grumbine, J. Xu, Mekong hydropower development, Science 332 (2011) 178–179.
[27] H. Huang, Z. Yan, Present situation and future prospect of hydropower in China, Renew. Sustain. Energy Rev. 13 (2009) 1652–1656.
[28] M.T.H. van Vliet, et al., Power-generation system vulnerability and adaptation to changes in climate and water resources, Nat. Clim. change 6 (2016a) 375–380.
[29] IPCC, Special Report on Renewable Energy Sources and Climate Change Mitigation, Working Group III Mitigation of Climate Change, Intergovernmental Panel on Climate Change, 2011.
[30] International Energy Agency, World Energy Outlook 2011, International Energy Agency, France, 2011.
[31] S. Salman, The Grand Ethiopian Renaissance Dam: Challenges and Opportunities, Center for Infrastructure Protection report, 2011.
[32] H. Ahlborg, M. Sjostedt, Small-scale hydropower in Africa: socio-technical designs for renewable energy in Tanzanian villages, Energy Res. Soc. Sci. 5 (2015) 20–33.
[33] FAO, Hydropower Resource Assessment in Africa, Food and Agriculture Organization of the United Nations, Rome, 2008.
[34] REN21, Renewables 2015 Global Status Report, 2015.
[35] X. Zhao, et al., A critical-analysis on the development of China hydropower, Renew. Energy 44 (2012) 1–6.
[36] National Renewable Energy Laboratory (NREL), Renewable Energy Policy in China: Financial Incentives, Colorado, 2004.
[37] Geoscience Australia and ABAR, Australian Energy Resource Assessment. Canberra, Australia, 2010.
[38] I. Yüksel, Renewable energy status of electricity generation and future prospect hydropower in Turkey, Renew. Energy 50 (2013) 1037–1043.
[39] C.R. Schilt, Developing fish passage and protection at hydropower dams, Appl. Animal Behav. Sci. 104 (2007) 295–325.
[40] A. Bartle, Hydropower potential and development activities, Energy Policy 30 (2002) 1231–1239.
[41] C.M. Stickler, et al., Dependence of hydropower energy generation on forests in the Amazon Basin at local and regional scales, Proc. Natl. Acad. Sci. U. S. A. 110 (2013) 9601–9606.
[42] B. Hadjerioua, Y. Wei, S. Kao, An Assessment of Energy Potential at Non-powered Dams in the United States, Wind and Water Power Program, Department of Energy, Washington DC, 2012.
[43] Management Information Services, 60 years of Energy Incentives – Analysis of Federal Expenditures for Energy Development, 2011.
[44] M. Islam, A. Fartaj, D. Ting, Current utilization and future prospects of emerging renewable energy applications in Canada, Renew. Sustain. Energy Rev. 8 (2004) 493–519.
[45] Oak Ridge National Lab (ORNL), 2014 Hydropower Market Report, U.S. Department of Energy, 2015.
[46] International Energy Agency, Renewable Energy Essentials: Hydropower, International Energy Agency, France, 2010.
[47] S. Karambelkar, Hydropower development in India: the legal-economic design to FuelGrowth? Nat. Resour. J. 57 (2017) 361.
[48] J. Xu, T. Ni, Integrated technological paradigm-based soft paths towards sustainable development of small hydropower, Renew. Sustain. Energy Rev. 70 (2017) 623–634.
[49] M.T.H. van Vliet, et al., Multi-model assessment of global hydropower and cooling water discharge potential under climate change, Glob. Environ. Change 40 (2016b) 156–170.
[50] K.E. Taylor, R.J. Stouffer, G.A. Meehl, An overview of CMIP5 and the experiment design, Bull. Am. Meteorol. Soc. 93 (2012) 485–498, 2012.
[51] R.H. Moss, et al., The next generation of scenarios for climate change research and assessment, Nature 463 (2010) 747–756.
[52] D. Vuuren, et al., The representative concentration pathways: an overview, Clim. Change 109 (2011) 5–31.
[53] Oak Ridge National Lab (ORNL), The International Satellite Land Surface Climatology Project, Initiative II (ISLSCP II), U.S. Department of Energy, 2017.
[54] J.T. Pedersen, et al., Hydrographs by Single Linear Reservoir Model, US Army Corps of Engineers, Davis, CA, 1980.
[55] H. Wu, et al., Automated upscaling of river networks for macroscale hydrological modeling, Water Resour. Res. 47 (2011), W03517.
[56] Y. Zhou, et al., A comprehensive view of global potential for hydro-generated electricity, Energy Environ. Sci. 8 (2015) 2622–2633.
[57] I.M. Held, B.J. Soden, Robust responses of the hydrological cycle to global warming, J. Clim. 19 (2006) 5686–5699.
[58] M.R. Allen, W.J. Ingram, Constraints on future changes in climate and the hydrological cycle, Nature 419 (2002) 224–232.
[59] P.A. O'Gorman, T. Schneider, The physical basis for increase in precipitation extremes in simulations of 21st-century climate change, Proc. Natl. Acad. Sci. U.S.A. 106 (2009) 473–477.
[60] R. Seager, et al., Model projections of an imminent transition to a more arid climate in southwestern North America, Science 316 (2007) 1181–1184.
[61] L. Gaudard, F. Avanzi, C.D. Michele, Seasonal aspects of the energy-water-nexus: the case of a run-of-the-river hydropower plant, Appl. Energy (2017), https://doi.org/10.1016/j.apenergy.2017.02.003 in press.
[62] C. Zhang, L.D. Anadon, Life cycle water use of energy production and its environmental impacts in China, Environ. Sci. Tech. 47 (24) (2013) 14459–14467.
[63] J. Zhang, L. Xu, X. Li, Review on the externalities of hydropower: a comparison between large and small hydropower projects in Tibet based on the CO_2,

equivalent, Renew. Sustain. Energy Rev. 50 (1–3) (2015) 176–185.

[64] J. Zhang, L. Xu, B. Yu, et al., Environmentally feasible potential for hydropower development regarding environmental constraints, Energy Policy 73 (5) (2014) 552–562.

[65] P.G. McCornick, S.B. Awulachew, M. Abebe, Water-Energy-Food synergies and tradeoffs: major issues and case studies, Water Policy 10 (2008) 23–36.

[66] The World Bank, Access to Electricity Data, The World Bank Group, 2015. http://data.worldbank.org/indicator/EG.ELC.ACCS.ZS/countries/ET?display=default.

[67] L. You, et al., What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach, Food Policy 36 (2011) 770–782.

[68] Water Resources and Environment Administration, Hydrological Analysis of Development Scenarios, Nam Ngum River Basin, Agence Française de Dévelopement and Asian Developing Bank, Vientiane, 2008.

[69] EPD, Power Projects in Lao PDR, Department of Energy Promotion and Development of the Ministry of Energy and Mines (EPD), Vientiane, 2012.

[70] G. Lacombe, et al., Are hydropower and irrigation development complements or substitutes? The example of the Nam Ngum River in the Mekong Basin, Water Int. 39 (2014) 649–670.

[71] X. Cai, D.C. McKinney, M.W. Rosegrant, Sustainability analysis for irrigation water management in the Aral Sea region, Agric. Syst. 76 (2003) 1043–1066.

[72] Karimov, A. et al, 2013, Reducing water and energy tradeoffs by increasing water and energy productivity: case study from the life irrigation areas of the Syrdarya River midstream, International Conference: Water in the Anthropocene: Challenges for Science and Governance. Bonn.

[73] C. Kuenzer, et al., Understanding the impact of hydropower developments in the context of upstream-downstream relations in the Mekong river basin, Sustain. Sci. 8 (2013) 565–584.

[74] S. Orr, et al., Dams on the Mekong River: lost fish protein and the implications for land and water resources, Glob. Environ. Change 22 (2012) 925–932.

[75] M.L. Wolfe, et al., Engineering solutions for food-energy-water systems: it is more than engineering, J. Environ. Stud. Sci. 6 (1) (2016) 172–182.

[76] T. Albrecht, A. Crootof, C. Scott, Trends in the Development of Water-Energy-Food Nexus Methods, XVI World Water Congress, International Water Resources Association, Cancun, Mexico, 2017.

[77] J.E. Houston, N.K. Whittlesey, Modeling agricultural water markets for hydropower production in the Pacific Northwest, West. J. Agr. Econ. 11 (1986) 221–231.

[78] S. Dhaubanjar, C. Davidsen, P. Bauer-Gottwein, Multi-objective optimization for analysis of changing trade-offs in the nepalese Water-Energy-Food nexus with hydropower development, Water 9 (2017) 162.